On Wind-Driven Mid-Latitude Convection in Ocean General Circulation Models

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Abstract

Several computational experiments were carried out with a state-of-the-art ocean general circulation model to identify the northward directed Ekman transport of Antarctic and Subantarctic origin surface water as a mechanism which forces mid-latitude convection. The results indicate that the wind-driven transport of water in the surface layer is most efficient at increasing the depth of convection in the southeast region of the ocean basin investigated. To the north of the latitude of maximum wind stress at about 50^o S, a deepening of the convectively mixed layer of more than 300 m is simulated if the wind forcing is doubled. In the real ocean, this identified mechanism of Ekman transport of cold and fresh water across the path of the Antarctic Circumpolar Current may contribute to the formation of Subantarctic Mode Water observed to the north of the Subantarctic Front of the Southern Ocean.

1. Introduction

Ocean general circulation models (OGCMs) adequately represent the formation of Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW) in the Southern Ocean (England et al., 1993; Ribbe and Tomczak, 1997). The simulated mechanism is that of warm tropical and subtropical origin surface water being advected with the gyre scale circulation and the western boundary currents southward. Along its path eastward across the mid-latitude ocean, heat is lost from the surface layer. Density instabilities are subsequently adjusted by shallow convective overturn. Evidence of this mechanism as simulated by OGCMs is found in the correlation of regions which are characterized by both oceanic heat loss and convection in mid-latitudes of the Southern Ocean (England et al., 1993). These model results are consistent with observations. SAMW and AAIW are the end products of a water mass formation mechanism, which is driven by shallow mid-latitude convection in the Southern Ocean (McCartney, 1977 and 1982; Schodlok et al., 1997).

In our understanding of the mid-latitude watermass formation process as simulated by OGCMs, it remains unclear if a contribution is made by wind-driven northward directed exchanges of Antarctic and sub-Antarctic origin surface water. England et al. (1993) identified a correlation between heat loss and mid-latitude convection within their model. They suggested that the northward transport of surface water across the pathway of the Antarctic Circumpolar Current (ACC) may contribute to the simulated temperature and salinity characteristics of SAMW. Ribbe and Tomczak (1997) found that the crossfrontal transport of Antarctic and sub-Antarctic origin surface water indeed modifies water mass characteristics in their model. They suggested further that the surface water exchange may actually drive the mid-latitude convection in OGCMs. This latter idea has been explored further in a series of computational experiments performed with an OGCM and results are reported in this paper. These experiments clearly establish a mechanism of wind-driven mid-latitude convection operating within OGCMs.

2. The Model and Design of the Computational Experiments

To identify the causes of mid-latitude convection, the Princeton Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model (MOM) was chosen (e.g. Bryan, 1969; Cox, 1989). In its present configuration, the model is comparable to that used by Goodman (1998). It uses only simplified topography similar to Cox's (1989) study, resolving the world ocean through three flat-bottomed basins and a connecting channel in the south. The model is of coarse resolution with 3.75^o and 4.5^o in zonal and meridional direction, and 20 vertical levels. In two control experiments, the model was forced with zonally and annually averaged mean Hellerman and Rosenstein (1983, referred to later on as HR83) winds. Heat and freshwater fluxes at the ocean surface drive the thermohaline component of the global ocean circulation. These fluxes were parameterized by applying a Haney type restoring boundary condition (Haney, 1971) which forces computed temperature and salinity to observed climatological mean values. For heat flux, for example, it takes the following form: $Q = \tau^{-1}\cdot(T_{ob} - T_{mo})$ [τ = restoring time scale, T_{ob} = observed temperature, T_{ob} = simulated temperature]. Both temperature and salinity are restored with a constant relaxation time scale of 50 days to annually and zonally averaged Levitus (1982). The Yin and Sarachik (1994) parameterization for convection is applied. The control experiments were integrated for 3000 years after which the general circulation within the model was assumed to be equilibrated.

The second control experiment employs the salinity enhancement of England et al. (1993) in which salinity in the extreme south is forced to a surface value of 35.0 psu. This experiment was carried out in order to draw a distinction between the two southern hemisphere regions of convective activity as simulated by coarse resolution OGCMs, i.e. mid-latitude and high-latitude convection. In many OGCMs, convection south of 50^o S is too deep and the likely causes have been discussed in the literature (e.g. England et al. 1993; Ribbe and Tomczak 1997). A second region of convective activity located north of about 50^o S, is referred to in this paper as the region of mid-latitude convection and is of further interest for the present study.

Two sets of short termed integrations were performed, each designed to study the impact of changes to the northward Ekman transport upon the depth of mid-latitude convection in the model. In each experiment, the model was integrated for a period of 10 years and initialized with output from the first control experiment. The two individual integrations of each set were carried out either with an enhanced (2 x HR83) or a weakened (0.5 x HR83) wind south of about 50^o S. In one set of experiments, conventional restoring to Levitus (1982) climatology was maintained, while the experiments of the second set were conducted with salinity restoring only. Instead of temperature restoring, heat fluxes diagnosed from the first control experiment were used. Due to the feedback mechanisms between oceanic and atmospheric temperatures, this form of mixed boundary condition is likely to be physically unrealistic. It prevents the advection of oceanic temperature anomalies and assumes instantaneous equilibrium between ocean and atmosphere temperatures. Nevertheless, this idealized situation has the advantage that it allows to separated between the two mechanisms which control mid-latitude convection, i.e. heat flux and northward directed Ekman transport.

While the model is of global coverage with simplified topography, only results from the south Indian Ocean basin are considered in this paper. This allows us to focus upon the mechanisms of mid-latitude convection. Longitudinal coordinates are model coordinates and do not correspond to the real ocean. All the figures shown here exhibit topographic features of idealized versions of the Antarctic continent in the south, the African continent in the west, the Australian continent between 55^o E and 90^o E, and the Indonesian Throughflow domain north of about 30^o S.

3 The Mechanism of Mid-Latitude Convection in an OGCM

The distribution of simulated heat fluxes and depths of convection computed in the first control experiment are shown in Fig. 1. Heat losses are at a maximum with about 100 Wm^{-2} in the western boundary current region (Fig. 1a). Warm subtropical origin surface water is advected southward joining the eastward directed circulation of the ACC. North of about 45^o S, a band of oceanic heat loss with values above 20 Wm^{-2} extends toward the east. After approaching a heat loss minimum centered at about 50^o S, heat losses increase in proximity to the Antarctic continent approaching values larger than 40 Wm^{-2}. The corresponding distribution of convection depths is shown in Fig. 1b. The shaded area is referred to as the region of mid-latitude convection. This region is located north of about 50^o S, the latitude that approximately coincides with the zone of maximum wind stress. South of this latitude, North Atlantic Deep Water up-wells into the surface layer while to the north Ekman pumping and mid-latitude convection ventilate the permanent thermocline of the subtropical gyres. Across the South Indian Ocean basin and to the north of the latitude of maximum wind stress, mid-latitude convection depths increase from about 50 m in the west to a maximum depth of about 800 m in the east.

Further to the south of 50^o S, the computed depths of convection are larger than 4000 m and are most likely overestimated. This particular short-coming is an intrinsic problem of many coarse-resolution OGCM and has been discussed previously (e.g. England et al., 1993). The salinity enhancement employed during the second control experiment alleviates this particular problem. Convective activity is reduced to about 2000 m south of 50^o S (Fig. 2b). The temperature surface forcing which drives convection in proximity to the Antarctic continent, i.e. the heat flux (Fig. 2a) in latitudes south of 50^o S, remains almost unchanged compared to the first control experiment (Fig. 1a). The reduction of convective activity is entirely due to an enhanced vertical flux of salt away from the surface. This increases subsurface salinity and density (Fig. 3), and in turn, reduces the depth of convection. The second control experiment further illuminates the distinction which can be drawn between the region of mid-latitude convection and that of the higher latitudes. Both regions are clearly separated by an area free of convective activity due to oceanic heat gains centered around 50^{o} S. Further to the north, convective activity is not greatly influenced by any subsurface density changes in the higher latitudes. This region is generally characterized by a stronger density stratification of the permanent thermocline. Heat fluxes remain almost unchanged north of about 50^{o} S.

In the following paragraphs, results from the two sets of short termed integrations using enhanced and weakened winds south of about 50^{o} S are discussed. The first set of experiments was conducted maintaining the restoring boundary condition for temperature and salinity. The heat fluxes and depth of convection of these experiments are shown in Fig. 4 and these should be compared to corresponding results from the first control experiment shown in Fig. 1. With an enhanced wind (Fig. 4a), both heat fluxes (left panel) and depths of mid-latitude convection (right panel) are modified. More cold Antarctic and sub-Antarctic origin surface water is transported northward across the path of the ACC due to an increased wind stress. The associated reduction in mid-latitude surface temperature north of about 50^{o} S results in a decreased oceanic heat loss. Due to the previously identified correlation between heat loss and the depth of mid-latitude convection (e.g. England et al., 1993), a reduction of the latter may be anticipated. This results from a reduced oceanic heat loss north of 50^{o} S. The reduction is off-set, however, by surface density instabilities which are a result of an enhanced Antarctic and sub-Antarctic origin surface water transport northward. This Ekman driven transport is particularly efficient in increasing the depth of mid-latitude convection in the southeast section of the Indian Ocean basin. East of about 30^{o} E, depths of mid-latitude convection

(Fig. 4a, right panel) are increased by several hundred meters compared to the control run (Fig. 1b).

The results from the weakened wind experiment (Fig. 4b), indicate changes to both heat fluxes (left panel) and depths of mid-latitude convection (right panel) due to a reduced Ekman transport of Antarctic and sub-Antarctic origin surface water. Mid-latitude heat losses are larger because less cold surface water is transported northward across the pathway of the ACC and into the southeast Indian Ocean. A maximum heat loss of more than 40 Wm^{-2} is simulated east of 50^o E. Despite this increased heat loss which in turn would result in an increased depth of mid-latitude convection, the latter is reduced due to a weakened northward transport of Antarctic and sub-Antarctic origin surface water by Ekman transport. This is particularly evident in the southeast Indian Ocean where, for example, the 300 m depth contour shifted by several degrees further to the east.

To further isolate the impact made by Ekman transport of Antarctic and sub-Antarctic origin surface water upon the depth of mid-latitude convection north of about 50^o S, a second set of short termed computational experiments was carried out. The model was forced with heat fluxes diagnosed from the first control experiment (Fig. 1a). This drastically reduces the advection of oceanic temperature anomalies within the model. Without these temperature anomalies, the effect of alterations in the wind on mid-latitude convection becomes more evident.

Newly computed depths of convection are shown in Fig. 5 and are to be compared with those shown in Fig. 1 and Fig. 4 (right panels). The top panel of Fig. 5 (Control) shows the depth of convection after the model was integrated for the additional period of 10 years, using diagnosed heat fluxes instead of temperature restoring as the surface boundary condition. The depth of convection remains unchanged (compare Fig. 1b and Fig. 5a). Only when forcing the model with an enhanced or weakened wind does the depth of convection alter significantly. During the enhanced wind experiment (Fig. 5b), mid-latitude convection depths of more than 600 m are simulated in the southeast Indian Ocean east of about 30^{o} E, reaching to more than 800 m further east. This is a significant increase of 200-300 m compared to the depth of mid-latitude convection simulated during the previous enhanced wind experiment which used the restoring boundary condition for temperature (Fig. 4a, right panel). The effect of a reduction in convective depths due to a reduced heat flux (Fig. 4a) is removed in the experiment forcing the model with diagnosed heat fluxes. In turn, the depth of mid-latitude convection increases.

In the weakened wind experiment, a further decrease of the depth of mid-latitude convection is observed (Fig. 5c). This is particularly evident in the southeast sector of the Indian Ocean basin. A reduction in convective depths of 300-400 m is simulated. This is associated with a reduced northward Ekman transport of Antarctic and sub-Antarctic origin surface water across the path of the ACC.

The changes to wind forcing in the Southern Ocean force a deepening or shallowing of mid-latitude convection depths, but also alter the simulated water mass characteristics. Temperature, salinity, and density anomalies (2xHR83 - Control Run) along a northsouth section from the enhanced wind experiment (2xHR) are shown for the southeast Indian Ocean basin in Fig. 6. North of about 50^{o} S, mid-latitude convection homogenizes the water column to depths of about 600 m. The locally formed water mass is cooler (Fig. 6a) as well as fresher (Fig. 6b) compared to the control run and the density is increased (Fig. 6c). With a weakened wind and a reduced surface layer water transport the locally formed water mass becomes warmer, saltier, and less dense.

4. Conclusions

The computational experiments reported clearly reveal that mid-latitude convection as simulated by OGCMs is partly driven by northward directed Ekman transport of Antarctic and sub-Antarctic origin surface water across the path of the ACC. Heat losses are at a maximum in the western part of the basin investigated while depths of mid-latitude convection progressively increase toward the east. The northward directed Ekman transport of Antarctic and sub-Antarctic origin surface water affects the depth of convection most sensitively in the southeast of the ocean basin investigated. Variations in wind result in changes to the characteristics of water masses formed in the mid-latitudes.

The computational experiments were carried out with an OGCM, which approximates the real ocean in a very simplified manner only. Nevertheless, the results indicate that it is not only heat fluxes that drive the formation of SAMW in the Southern Ocean, but also Ekman transport may determine SAMW characteristics and drive mid-latitude convection in the real ocean. Future work will attempt to quantify these two forces of mid-latitude convection.

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Figure Legends

Figure 1: Results of the first control experiment: (a) heat fluxes (Wm^{-2}) contoured in intervals of 20 (Wm^{-2}), regions of oceanic heat loss are shaded; (b) depth of convection (m) contoured in intervals of 50, 100, 200, 300, 400, 500, 600, 800, 1000, 2000, and 4000 m; the mid-latitude convection region is shaded down to depths of 800 m.

Figure 2: Results of the second control experiment: (a) heat fluxes, and (b) depth of convection (m). Contouring and shading as in Figure 1.

Figure 3: Mean density profile computed for the south Indian Ocean basin only. Data for both profiles are form the 1st and 2nd control experiment.

Figure 4: Results from the first set of short termed integrations initialized with output from the first control experiment: (a) heat fluxes (Wm^{-2}) (left panel), and depth of convection (m) (right panel) of the enhanced wind experiment; (b) heat fluxes (Wm^{-2}) (left panel), and depth of convection (m) (right panel) of the weakened wind experiment. Contours and shading as in Figure 1.

Figure 5: Results from the second set of short termed integrations initialized with output from the first control experiment. Shown is the depth of convection (m) computed during the: (a) control, (b) enhanced, and (c) weakened wind

experiment. In all integrations, only salinity was restored to Levitus data. Heat fluxes were diagnosed from the first control experiment and used instead of temperature forcing.

Figure 6: (a) Temperature, (b) salinity, and (c) density (σ_t) anomalies computed as the difference between the enhanced wind experiment (2xHR) and the first control run. Anomalies within the SAMW depth range have been shaded. Contour intervals are 0.1 ^{o}C for temperature, 0.01 for salinity, and 0.01 kg$\cdot$m^{3} for density.